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NaTech Scenarios Caused by Flooding: Evaluation of Accident Frequency by the Use of Fragility Models

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Natural events impacting on process plants may lead to severe technological accidents. These events are usually defined as NaTech events (Natural Hazard Triggering Technological Disasters). In order to derive the frequencies of accident scenarios associated to NaTech events for QRA (Quantitative Risk Assessment) implementation, a critical issue is the availability of equipment vulnerability models. The aim of the present study was to present a vulnerability model for the assessment of failure probability of atmospheric vessels involved in flooding events. The vulnerability model was based both on the severity of the natural event and on the construction features of the equipment. In order to explore the model features and its potentialities, the application to case-studies was carried out analysing an actual industrial layout. The results obtained confirmed that NaTech scenarios caused by floods may have an important influence on risk assessment and management of industrial facilities.

1. Introduction

Natural events may impact on process installations triggering severe technological accidents (NaTech events) by damaging process and storage equipment (Young at al., 2004), and leading to the loss of containment (LOC) of hazardous materials (Cozzani et al., 2010). Specific studies (Salzano et al., 2009) demonstrated that NaTech events often occurred in the past with severe consequences in industrial facilities and treatment plants (Panico et al., 2013). This was confirmed by the analysis of past accidents (Renni et al., 2010).

The implementation of NaTech scenarios in the framework of Quantitative Risk Assessment (QRA) is a critical task (Campedel et al., 2008), especially for facilities located in areas affected by natural hazards (flooding, earthquakes, tsunami, etc.) (Cruz et al., 2006). Previous studies focused on the NaTech implementation in QRA (Antonioni et al., 2009), highlighting that the more crucial step is the definition of reliable tools for the estimation of the NaTech scenarios frequency (Cozzani et al., 2013). The present study focused on a methodology for evaluation of the accident frequency induced by flooding on industrial equipment by the use of a specific vulnerability model, which was developed for an equipment category often involved in accidents triggered by flooding (Cozzani et al., 2010): atmospheric vertical cylindrical vessels for the storage of liquids.

The impact mode of flooding was first schematized on the basis of the analysis of past accidents in industrial facilities involved in floods. A mechanical model was then developed, based on the comparison between the flooding intensity and the resistance of a vessel. The mechanical model, validated against the available data obtained from past accident records, was applied to generate an extended data set of failure conditions, aimed at the calculation of simplified correlations able to yield a conservative estimation of equipment failure conditions and, thus, of failure probability.

The proposed vulnerability model was finally applied for the analysis of an industrial lay-out, in order to test the validity of the model and highlight the contribution of NaTech-induced accidents to the risk profile of a facility.

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2. Methodology

The aim of the present study was to present a methodology for the evaluation of failure probability of atmospheric vertical vessels involved in flooding events and thus to estimate the associated frequency for QRA implementation. The methodology, divided in six steps, was based on the definition of equipment-specific vulnerability functions taking into account both the severity of the natural event and the construction features of the equipment. The following sections illustrate the steps of the methodology.

2.1 STEP 1: Schematization of the reference equipment

From the analysis of past accidents triggered by floods (Cozzani et al., 2010), it was evidenced that above ground atmospheric storage tanks are the process items that were more frequently damaged in flood events. This vessel type consists in a vertical cylinder with fixed or floating roof operating at atmospheric pressure (see the scheme in Figure 1). Tanks bottom is typically flat and directly fixed to the ground with a dap joint. This type of vessel is mainly used for liquid storage at near-atmospheric pressure.

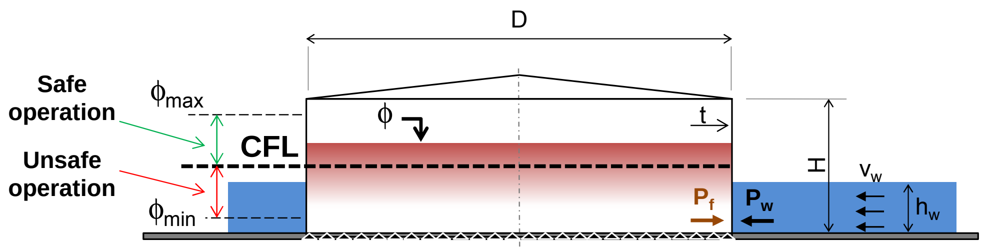


Figure 1: schematization of atmospheric storage tanks involved in flooding events.

Table 1 reports the features of the vessels considered in the present study. A specific vessel database was built (Landucci et al., 2012). Vessel geometries and design data were obtained from API standard 650, while the volumes and diameters were based on data gathered from several oil refineries.

Table 1: reference vessel geometries considered in the present study. See Figure 1 for vessel sketch and parameters identification.

Vessel class	D (m)	H (m)	t (mm)	Capacity (m^3)	P_{cr} (Pa, see Eq.5)
Small capacity	3-42	3.6–18	5–12.5	< 5,000	6,932–19,285
Medium capacity	21-54	3.6–16.2	12.5	5,000 – 10,000	5,180–11,171
Large capacity	48-66	3.6-7.2	12.5-15	>10,000	4,361-12,666

2.2 STEP 2: Characterization of flooding conditions

The elements needed for the characterization of the flooding impact are essentially the flooding frequency and severity. The flood frequency has been estimated using the return period (t_r, given by hydrological studies or available at local competent authorities) as follows:

$$f = 1/t_r \qquad (1)$$

Several possible modalities of flood impact must be distinguished (slow submersion and high depth wave; moderate speed wave; high speed wave with limited depth, etc). Hence, the flood severity was quantified by two parameters: water depth (h_w) and water speed (v_w).

On the basis of available data on past events reasonable ranges of both h_w and v_w were collected and reported in Table 2. Table 2 also summarizes the flooding conditions used for the analysis of the case studies (see Section 3).

Table 2: flooding conditions selected for the present study.

Flooding conditions	Height h_w (m)	Velocity v_w (m/s)	Return period t_r (y)	Frequency f (y^{-1})
Range for the present study	0 – 4	0 – 3.5	50 – 500	2.0×10^{-3} - 2.0×10^{-2}
W1 (case study 1)	0.7	0.7	50	2.0×10^{-2}
W2 (case study 2)	1.8	0.25	500	2.0×10^{-3}

2.3 STEP 3: Mechanical model set up

Figure 1 schematizes the forces acting on the atmospheric vessels when impacted by a flood wave. The external load present on the tank shell, namely P_w, is obtained as the sum of a “static” pressure component P_{ws} and of a “dynamic” pressure component P_{wd} as follows:

$$P_w = P_{ws} + P_{wd} = \rho_w \, g \, h_w + \tfrac{1}{2} \rho_w \, k_w \, v_w^2 \qquad (2)$$

where g is the gravity constant (9.81 m/s^2), ρ_w is the density of the floodwater and k_w is the hydrodynamic coefficient (Gudmestad and Moe, 1996). The static pressure component P_{ws} is due to the hydrostatic load of the floodwater, while the dynamic component P_{wd} is due to the drag force associated to the kinetic energy of the wave. A constant temperature of 293 K and an atmospheric pressure of 1.01 bar were assumed in the present study, thus the fluid properties are considered constant in the above relations.

The internal pressure of the tank (P_f), related to the hydrostatic pressure of the internal liquid hold up, has an important role in the evaluation of the resistance of the tank to flood external pressure. The maximum P_f value, at the bottom of the vessel, may be expressed as follows:

$$P_f = \rho_f \, g \, H \, \phi \qquad (3)$$

where ρ_f is the density of the inner fluid, H is the height of the tank and ϕ is the filling level. Therefore, the net pressure P_{net} on the vessel shell may be derived from a simple force balance:

$$P_{net} = P_{ws} + P_{wd} - P_f \qquad (4)$$

The external P_{net} acting on the vessel may cause the structural integrity loss by instability (Timoshenko and Gere, 1961) and typically affects atmospheric vessels. Instability may occur if the P_{net} reaches a critical value, P_{cr} (critical pressure). P_{cr} depends only on the vessel geometry and on the construction material (independent from the loading conditions), and may be calculated by the following expression:

$$P_{cr} = \frac{2\,E\,t}{D} \left\{ \frac{1}{\left(n^2-1\right)\left[1+\left(\frac{2nH}{\pi D}\right)^2\right]^2} + \frac{t^2}{3(1-\nu^2)D^2}\left[n^2 - 1 + \frac{2n^2-1-\nu}{\left(\frac{2nH}{\pi D}\right)^2 - 1} \right] \right\} \qquad (5)$$

in which E and ν are respectively the elastic modulus and Poisson’s ratio of the construction material; t, D, H the vessel thickness, diameter and height, and n is an integer number defined as follows:

$$n \geq \left(\frac{\pi}{2}\right)\left(\frac{D}{H}\right) \quad n \geq 2 \qquad (6)$$

Therefore, given a set of vessels of interest, the P_{cr} is evaluated and compared with the P_{net}, which results from different flooding and storage conditions. The failure for instability of atmospheric vessels is hence predicted by the model if P_{cr} becomes greater or equal respect to P_{net}.

Table 3: parameters assumed for the present study (Landucci et al., 2012). Ranges are given for the typical flooding conditions (Rijkswaterstaat, 2005) and for the materials commonly used for atmospheric vessels construction, based on API Standard 650 (API, 2003).

Parameter	Present study	Minimum value	Maximum value
k_w	1.8	1.6	2.2
ρ_w (kg/m^3)	1,100	1,000	1,200
E* (GPa)	205	190	210
ν*	0.29	0.26	0.3
ρ_{f0} (kg/m^3)	1,000**	-	-

(* Function of the vessel material; ** Reference density for vessel design)

The failure model may be used to evaluate the resistance of vessels undergoing different flooding conditions (represented by different values of v_w and h_w) considering different storage/processing conditions (e.g., internal fluid density and filling level). Model results are discussed in the following, while Table 3 collects the values assumed for model parameters and the possible range of values used for model validation and sensitivity analysis (Section 2.4).

2.4 STEP 4: Model validation and sensitivity analysis

Data on flood damage to equipment items are scarce and not detailed, often providing only qualitative information (Krausmann et al. 2011). Hence, in order to validate the model, a damage threshold was derived from a previous study based on an extended past accident data analysis (Rijkswaterstaat, 2005). The damage threshold was the value of external pressure P_w below which vessel damage and/or loss of containment was never reported in past accidents. This resulted equal to 9.4 kPa, associated to a flood wave with a velocity of 2 m/s and a maximum height of 0.5 m (Rijkswaterstaat, 2005). Failure model predictions may be validated comparing the resistance of the vessels considered a tank database (see Table 1) with respect to the damage threshold considered. Due to the uncertainties in the input parameters, both referred to construction steel and flooding properties the validation was carried out for the values assumed in the present study, for the maximum and minimum range parameters see (Table 3).

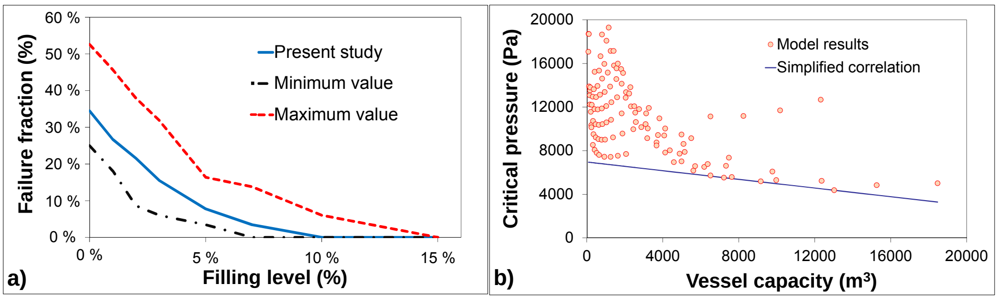


Figure 2: a) failure fraction of the tanks subjected to the reference flood impact conditions as a function of the filling level for different sets of input parameters; b) envelope correlation for the straightforward estimation of the vessel critical pressure

Figure 2a shows the failure fraction (%) of atmospheric vessels subjected to the reference flooding conditions. Considering the input parameters adopted for the present study (e.g., data represented by the solid line) few vessels failed even when empty (about 35 % predicted failure fraction). Moreover, changing the input parameters, according to the credible range reported in Table 3, the predicted failure fraction reaches zero for filling level values higher than 15 %. Thus, the validation evidenced that failure conditions predicted by the model are robust respect to the choice of credible input parameters and in sufficient agreement with the available literature data.

2.5 STEP 5: Model application and definition of a simplified envelope correlation

In order to obtain simplified correlations for a straightforward estimation of the vessel failure and to derive a vulnerability model, the filling level of the vessel was considered as the critical parameter. Since the geometry of the storage vessel and the characteristics of the stored substance are defined, the only operating parameter which affects vessel resistance to flooding is the filling level. Thus, a Critical Filling Level (CFL) of a vessel may thus be defined as the minimum ϕ value able to ensure the tank resistance to a flood wave of a given intensity:

$$CFL = \frac{P_{ws} + P_{wd} - P_{cr}}{\rho_f gH} \qquad (7)$$

The CFL may be obtained by Eq. 7 if the value of P_{cr} is calculated applying Eq. 5. However, in order to obtain a straightforward P_{cr} estimation, the following correlation was obtained as a function of the vessel capacity C by the analysis of the extended dataset of failure conditions (see Figure 2b):

$$P_{cr} = k_1 C + k_2 \qquad (8)$$

where k_1=-0.199, k_2=6950, C is expressed in m^3 and P_{cr} in Pa. The correlation underestimates the minimum P_{cr} for each vessel capacity leading to shortcut evaluation on the safe side. The maximum error of the correlation (around 40%) is related to smaller vessels, which are likely to trigger less relevant and less hazardous release scenarios due to the limited fluid inventory.

2.6 STEP 6: Assessment of vessel vulnerability and damage frequency

Figure 1 shows the approach to the assessment of atmospheric tanks vulnerability to flooding (namely Ψ). If the filling level is lower than the CFL (marked by a dashed bold line in Figure 1), the tank is in the "unsafe conditions" zone since the vessel is not able to resist to the external pressure. In the present approach, for the sake of simplicity, a linear distribution of possible operative filling levels between ϕ_{min} (=1 %) and ϕ_{max} (=75 %) is assumed in the definition of Ψ. On the basis of these considerations, the vessels damage probability Ψ is derived by the ratio between the "unsafe conditions" with respect to all the possible operative conditions, finally obtaining the damage frequency as follows:

$$f_{LOC} = f \times \Psi = f \times \frac{CFL - \phi_{min}}{\phi_{max} - \phi_{min}} \quad (9)$$

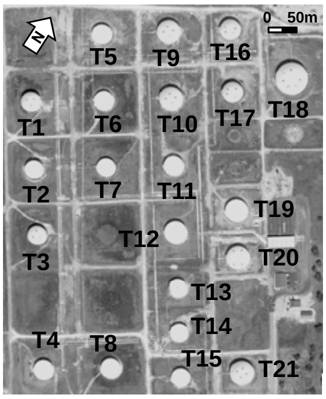
where f (1/y) is the frequency of flooding of a given intensity (v_w; h_w).

3. Results and discussion

3.1 Definition of the case studies

In order to test the methodology in a typical QRA framework, a vulnerability analysis of a tank farm (Figure 3) was carried out to assess the expected damage probability and the associated hazardous materials release frequencies (f_{LOC}) caused by flood conditions. Figure 3 summarizes the features of the vessels analysed and reports the densities of the stored substances. Two reference flooding scenarios were considered, as summarized in Table 2:

- Case study 1: low severity flooding (W1 conditions) with low return period and thus high frequency;
- Case study 2: high severity flooding (W2 conditions) with high return period and thus low frequency.



ID tank	Capacity (m^3)	Liquid density (kg/m^3)	Diameter (m)	Height (m)	Thickness (mm)
T1-T2	5494	850	36	5.4	12.5
T3-T4	7325	700	36	7.2	12.5
T5	9156	850	36	9	12.5
T6-T7	5494	1100	36	5.4	12.5
T8	18086	1100	40	14.4	23
T9-T10	7478	800	42	5.4	12.5
T11	7325	1100	36	7.2	12.5
T12	7478	850	42	5.4	12.5
T13	6359	850	30	9	12.5
T14-T15	7630	900	30	10.8	12.5
T16	3662	950	36	3.6	10.1
T17	18086	650	40	14.4	23
T18	15260	650	60	5.4	12.5
T19	18086	850	40	14.4	23
T20-T21	9970	650	42	7.2	12.5

Figure 3: a) layout for the two case studies; b) features of the vessels and stored fluid density.

3.2 Vessels vulnerability and failure frequencies

Table 4 reports the vulnerability values obtained for the tanks applying the CFL approach. Both model and correlation results are reported. As expected, in the case of the low severity flood, with limited water height and velocity (e.g., case study 1) lower values of ψ (lower than 15 %) are obtained with both model and correlations. On the contrary, in the case of more severe flooding (e.g., case study 2), all the tank farm is subjected to severe damages. Table 4 shows also the evaluated LOC frequencies calculated for each tank on the basis of vulnerability assessment for the two case studies (f_{LOC}). As shown in Table 4, LOC frequency values range between 9×10^{-5} and 3×10^{-3} 1/y. As it can be seen, despite the lower vulnerability values, flooding conditions W1 lead to higher f_{LOC} values due to low return period, thus presenting the higher contribution to the risk profile of the tank farm. It should be remarked that LOC events due to internal failure causes usually have comparable or even lower frequencies (Uijt de Haag and Ale, 1999) respect to the values calculated for the case study, confirming that in flood-prone zones, NaTech scenarios triggered by floods may have a significant impact on the tank farm safety management.

4. Conclusions

A model was developed to calculate the damage probability of atmospheric vessels in flood events. The modeling approach was validated against literature data, identifying the more critical parameters affecting vessel resistance. The model allowed determining an extended dataset of failure conditions which was used to obtain a simplified correlation for vessels failure and damage probability. Finally, the methodology was applied for the analysis of case studies. The results obtained confirmed that NaTech scenarios caused by floods may affect the risk profile of industrial facilities due to the significant values of expected damage frequencies.

Table 4: Results of the case study: vessels vulnerability (ψ, %) and expected failure frequency (f_{LOC}, 1/y) as a function of the critical filling level (CFL, in %). NF = failure is not predicted by the model

ID Vessel	Case study 1						Case study 2					
	Model			Correlations			Model			Correlations		
	CFL (%)	ψ (%)	f_{Loc} (1/y)	CFL (%)	ψ (%)	f_{Loc} (1/y)	CFL (%)	ψ (%)	f_{Loc} (1/y)	CFL (%)	ψ (%)	f_{Loc} (1/y)
T1-T2	1.0%	NF	NF	4.8%	5.2%	1.04×10^{-3}	23.0%	29.7%	5.89×10^{-4}	30.3%	39.6%	7.83×10^{-4}
T3-T4	2.9%	2.6%	5.15×10^{-4}	5.2%	5.6%	1.12×10^{-3}	26.1%	33.9%	6.71×10^{-4}	28.3%	36.9%	7.31×10^{-4}
T5	3.8%	3.8%	7.59×10^{-4}	3.9%	3.9%	7.78×10^{-4}	19.1%	24.4%	4.83×10^{-4}	19.1%	24.5%	4.85×10^{-4}
T6-T7	1.0%	NF	NF	3.7%	3.7%	7.42×10^{-4}	17.8%	22.7%	4.49×10^{-4}	23.4%	30.3%	5.99×10^{-4}
T8	1.0%	NF	NF	3.0%	2.7%	5.45×10^{-4}	4.5%	4.7%	9.23×10^{-5}	10.4%	12.7%	2.51×10^{-4}
T9-T10	1.6%	0.9%	1.75×10^{-4}	6.1%	6.9%	1.37×10^{-3}	28.7%	37.4%	7.40×10^{-4}	33.1%	43.4%	8.59×10^{-4}
T11	1.8%	1.1%	2.30×10^{-4}	3.3%	3.1%	6.16×10^{-4}	16.6%	21.1%	4.17×10^{-4}	18.0%	23.0%	4.55×10^{-4}
T12	1.6%	0.7%	1.49×10^{-4}	5.7%	6.4%	1.28×10^{-3}	27.0%	35.1%	6.95×10^{-4}	31.1%	40.7%	8.07×10^{-4}
T13	1.7%	0.9%	1.88×10^{-4}	3.1%	2.9%	5.78×10^{-4}	16.9%	21.6%	4.27×10^{-4}	18.4%	23.5%	4.65×10^{-4}
T14-T15	2.6%	2.2%	4.31×10^{-4}	2.7%	2.3%	4.69×10^{-4}	14.6%	18.4%	3.64×10^{-4}	14.7%	18.6%	3.68×10^{-4}
T16	1.0%	NF	NF	5.4%	6.0%	1.19×10^{-3}	32.9%	43.0%	8.52×10^{-4}	39.5%	52.1%	1.03×10^{-3}
T17	1.0%	NF	NF	5.1%	5.5%	1.11×10^{-3}	7.5%	8.8%	1.75×10^{-4}	17.6%	22.4%	4.43×10^{-4}
T18	9.3%	11.3%	2.25×10^{-3}	12.0%	14.8%	2.97×10^{-3}	42.6%	56.2%	1.11×10^{-3}	45.2%	59.8%	1.18×10^{-3}
T19	1.0%	NF	NF	3.9%	3.9%	7.85×10^{-4}	5.8%	6.4%	1.27×10^{-4}	13.4%	16.8%	3.33×10^{-4}
T20-T21	6.0%	6.8%	1.35×10^{-3}	6.7%	7.7%	1.54×10^{-3}	30.9%	40.4%	8.01×10^{-4}	31.6%	41.4%	8.20×10^{-4}

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